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Methodology for Designing and Developing a New Ultra-Wideband Antenna Based on Bio-Inspired Optimization Techniques

by Canh Ly, Nghia Tran, and Ozlem Kilic

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Methodology for Designing and Developing a New Ultra-Wideband Antenna Based on Bio-Inspired Optimization Techniques

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14. ABSTRACT The rapid designs and developments of a new ultra-wideband (UWB) antenna are needed for imaging radar technologies for deployment in small unmanned air and ground vehicles for a variety of US Army applications. In this research, the design and development of a new UWB antenna is investigated. Bio-inspired optimization techniques such as particle swarm optimization and full-wave numerical techniques are utilized to optimize all desired antenna parameters in this report.					
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1. Introduction

The US Army Research Laboratory (ARL) is moving toward developing highly capable imaging radar technologies for deployment in small unmanned air and ground vehicles for a variety of Army applications. This requires the rapid design and development of a new ultra-wideband (UWB) antenna. This antenna will save tremendous engineering time and help to shape the future of the airborne as well as ground-penetrating synthetic aperture radar (GPSAR) systems for the Army generally and specifically for the ARL mission program to detect buried improvised explosive devices (IEDs) and surface off-the-road targets such as explosively formed penetrators (EFPs). Also, the development of this antenna will be utilized for other major applications including sensing through the wall and detecting targets under the tree canopy. This research is being conducted under an Open Campus Collaborative Research and Development Agreement between ARL and The Catholic University of America (ARL-CUA 16-84, dated 21 December 2016).

In the early stages of this project, the new-design antenna will operate from 300 MHz to 3 GHz with a low return loss (less than -10 dB). The antenna should also be small, low-profile, and compact.

To achieve all desired parameters, bio-inspired optimization techniques combined with full-wave numerical methods are implemented. In Section 2, the methodology of this research is presented, followed by tools in Section 3 that mention optimization and numerical methods used in this research. Section 4 includes all possible designs and some preliminary results.

2. Methodology

Figure 1 describes the optimization technique for designing a new UWB antenna. The steps are as follows. First, the range of antenna parameters range are defined and particle positions and velocities are initialized. The second step is to adjust the position of antenna and query the database. In step 3, according to the query result, if the same particle position exists in database, then return the corresponding result as the current particle fitness value. Otherwise, there are 2 additional steps: 1) MATLAB will use methods of moment (MoM) to run and return the minimal value of antenna return loss as the fitness value of particles and 2) storing the position and fitness value to the database. The personal best (pBest) is updated in step 4. The global best (gBest) is chosen from all personal bests. The next step is to judge the objective function or the maximum number of iterations meet termination criteria. If the termination condition is satisfied, the output is the gBest; otherwise repeat step 2.

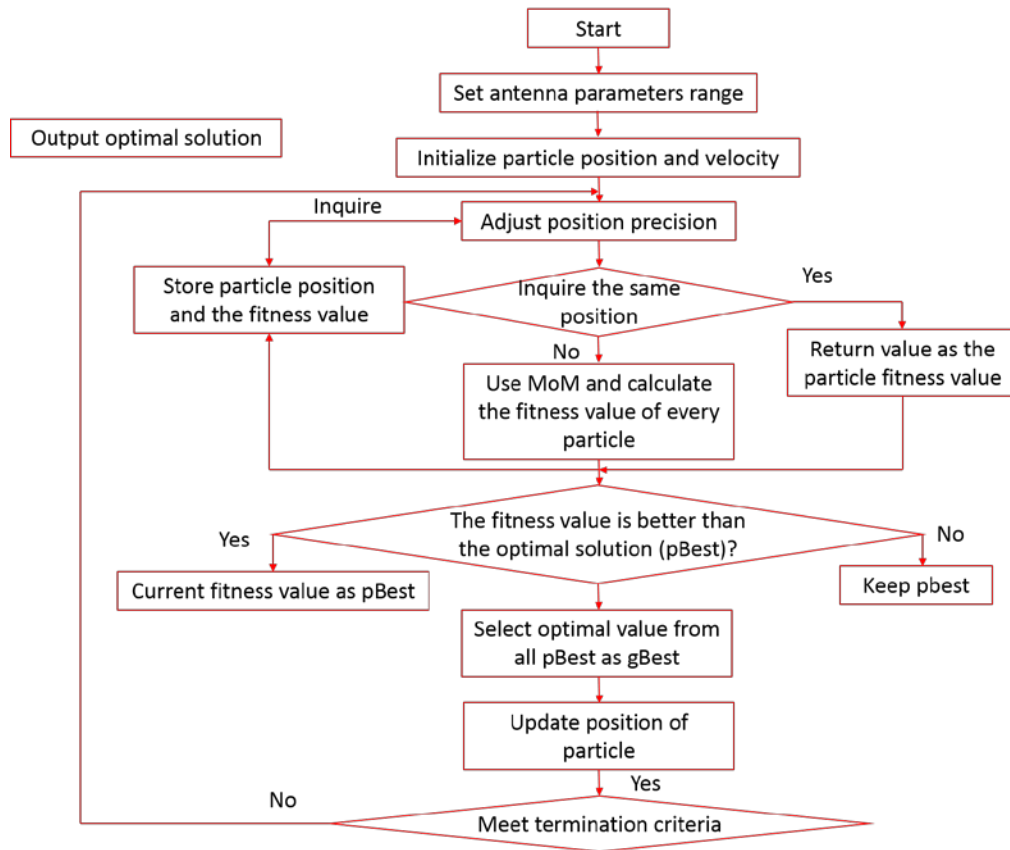


Fig. 1 Flowchart of the new UWB design

3. Tools

We have investigated different optimization techniques for design and development of a new UWB antenna. These include ant colony optimization,¹ artificial immune system,² and particle swarm optimization (PSO).^{3,4} For this report, we chose the bio-inspired optimization technique for our investigation.

3.1 Bio-Inspired Optimization Techniques: Particle Swarm Optimization (PSO)

Bio-inspired optimization techniques involve independent sampling of the optimization space by a number of agents (e.g., bees in a swarm for PSO) using intelligence-based random search.⁴ The search is iterated until a desired solution or the maximum allowable duration is reached. Each iteration adds more intelligence to the heuristic search by taking advantage of the sampled data. How good a given location is for a given agent is determined by the fitness function, which compares the sampled point against desired criteria.

PSO is one of the best-known bio-inspired optimization algorithms and operates on the basis of the principles shown in Fig. 2. It emulates the swarm behavior of bees in their search for the best food source in a field. A set of bees sample the optimization space iteratively until the desired solution criteria are met. Bees make their decisions on where to go next as they search for the best location on the basis of the current collective intelligence of the swarm (global best, g_{bn}) and their personal experiences (personal best, p_{bn}).

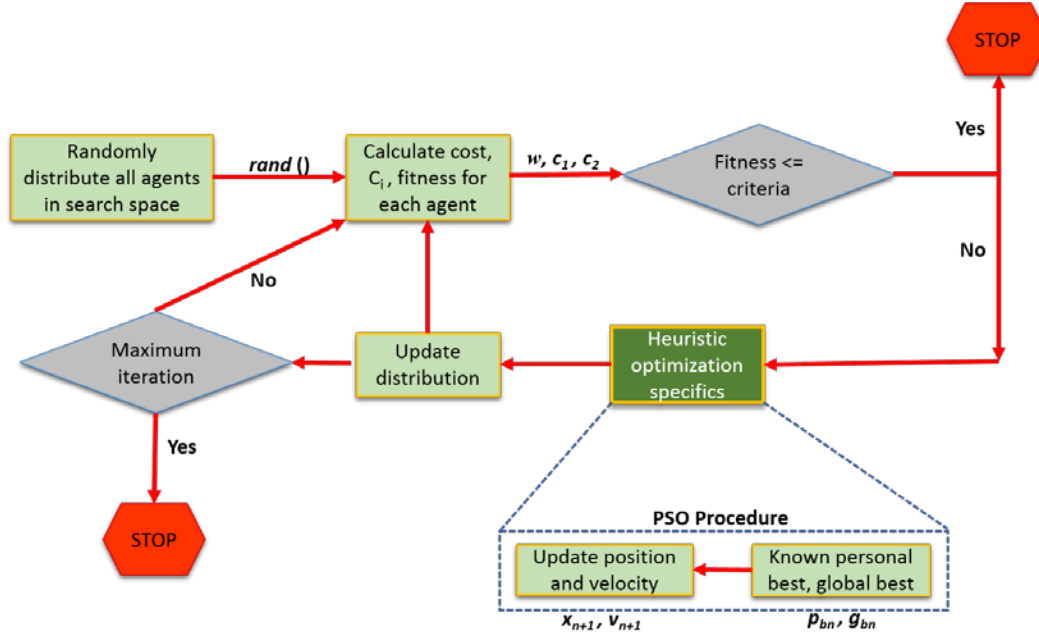


Fig. 2 PSO flowchart

The velocity (both magnitude and direction) that determines the next position of an agent is based on these 2 factors, g_{bn} , and p_{bn} , in a random fashion as shown in Eqs. 1 and 2:

$$v_{n+1} = w * v_n + c_1 rand() \times (p_{bn} - x_n) + c_2 rand() \times (g_{bn} - x_n) \quad (1)$$

and

$$x_{n+1} = x_n + \Delta t \times v_{n+1}, \quad (2)$$

where v_n is the velocity of the particle in the n th dimension and x_n is the particle's coordinate in the n th dimension. w , c_1 , and c_2 are scaling factors that determine the relative p_{bn} and g_{bn} . In this project, $c_1 = 2$, $c_2 = 2$, and $0.4 < w < 0.9$ were chosen. The random number function, $rand()$, returns a number between 0.0 and 1.0. Once the velocity has been determined, it is simple to move the particle to its next location. New coordinate x_n is computed for each of the N dimensions according to

Eq. 2. The fitness function is computed corresponding to its application. For example, in this study, the fitness function for each bee is the maximum return loss from 300 MHz to 3 GHz as shown in Eq. 3. Even though in this report the fitness function is only the return loss S_{11} within the desired bandwidth, the antenna gain and 3-dB beam-width constraints will also be included in the future investigations to complete the project.

$$fitness = \max(S_{11})|_{0.3GHz < frequency < 3GHz}, \quad (3)$$

where

$$S_{11} = -20 \log_{10} \left| \frac{Z_{load} - Z_{source}}{Z_{load} + Z_{source}} \right|. \quad (4)$$

3.2 Full-Wave Electromagnetic Modeling: Methods of Moment

To calculate the fitness functions from PSO, we need to have the full-wave electromagnetic scattering model. Currently, there is a wide range of techniques, such as the finite element method, boundary element method, and MoM.² For our antenna design, MoM technique is ideal and can be solved numerically using the electric-field integral-equation formulation of the MoM, which is a well-established full-wave analysis based on meshing the geometry into coalescent triangles and using the expansion of the surface currents into Rao-Wilton-Glisson basis functions.⁵ The expansion results in a linear system shown in Eq. 5 and Fig. 3.

$$[Z][I] = [V], \quad (5)$$

where $[V]$ is the source function, $[I]$ is the current unknown, and $[Z]$ is the impedance matrix. The impedance matrix dimensions are $N \times N$, where N is the number of nonboundary edges in the triangular mesh. The impedance matrix is computed on the basis of the mesh geometry and all interactions between source edge and observation edge. The unknown currents are calculated using $[I] = [Z]^{-1} \cdot [V]$, where the source vector $[V]$ is computed on the basis of the geometry and the excitation fields at each triangle.

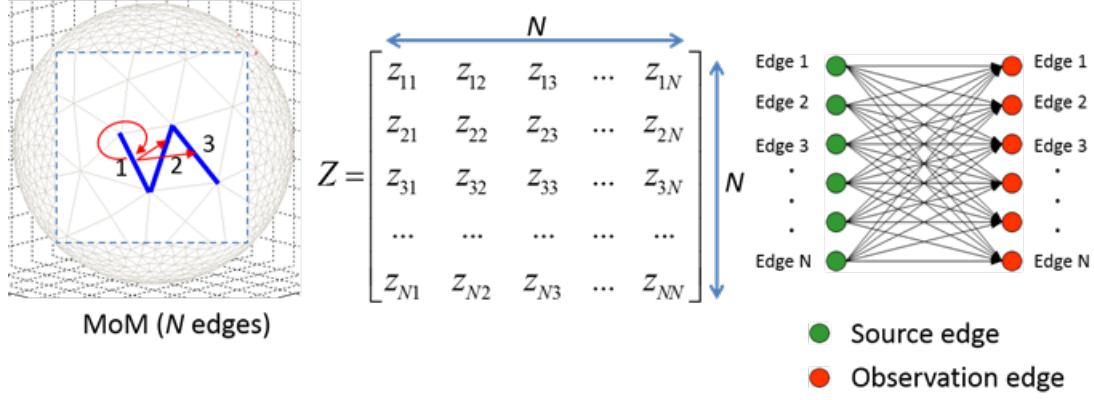


Fig. 3 Method of moment

4. Designs and Preliminary Results

For the early phase of this project, we have tried to optimize the antenna design to achieve the return loss S_{11} below -10 dB from 300 MHz to 3 GHz. In this section, 2 designs are presented and investigated. Simulation and experimental results are also shown as preliminary results.

4.1 Rectangular Monopole Patch Antenna

The first proposed antenna is the elliptical monopole antenna fed by a tapered co-planar plane wave (CPW) feeder. However, the result of return loss S_{11} from this antenna after optimization is not converged. As a result, the rectangular monopole is utilized instead of the elliptical monopole antenna. The design parameters of a CPW-fed rectangular monopole antenna is optimized using PSO combined with the high-frequency commercial software FEKO. The bandwidth is 0.3–3 GHz for $S_{11} < -10$ dB. Topology of the objective antenna is parameterized and depicted in Fig. 4. The patterns in orange are copper. All of the metal patterns are fabricated on the single side of the substrate, and there is no ground on the other side. The thickness of the substrate is 1.524 mm, and the relative permittivity is 4.4. Simulated parameters of the UWB antenna optimization are listed in Table 1. In this design we optimized 2 parameters, namely length “a” and width “b” of the rectangular monopole. We used 50 bees and ran 200 iterations with 10 frequencies from 0.3 to 3 GHz. For each bee, we randomized a and b and used FEKO to create the shape of the antenna and return the loss. For each frequency, we have the set of a and b with the best return loss. The optimized design parameters are $a = 133.29$ mm and $b = 39.54$ mm. The prototype of this antenna was also fabricated, as shown in Fig. 5, with FR4, $\epsilon = 4.7$, single-sided substrate.

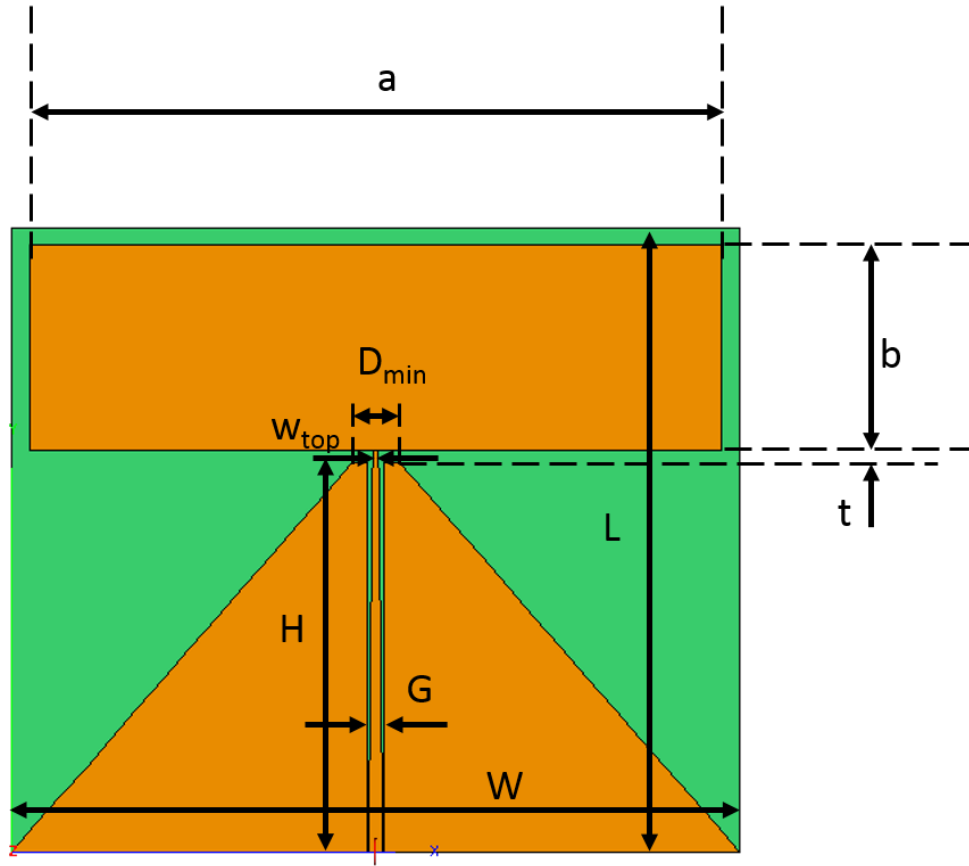


Fig. 4 Rectangular monopole patch antenna

Table 1 Simulated parameters of the rectangular monopole antenna

Fixed parameter (mm)	$W = 140, L = 120, H = 75, G = 3, W_{bot} = 2.7, D_{min} = 9, W_{top} = 1.2, t = 2.3, \epsilon = 4.4$
Optimization parameter	a, b
Number of agents	50
Maximum iterations	200
Boundaries	$600 < a < 140, 10 < b < 45$

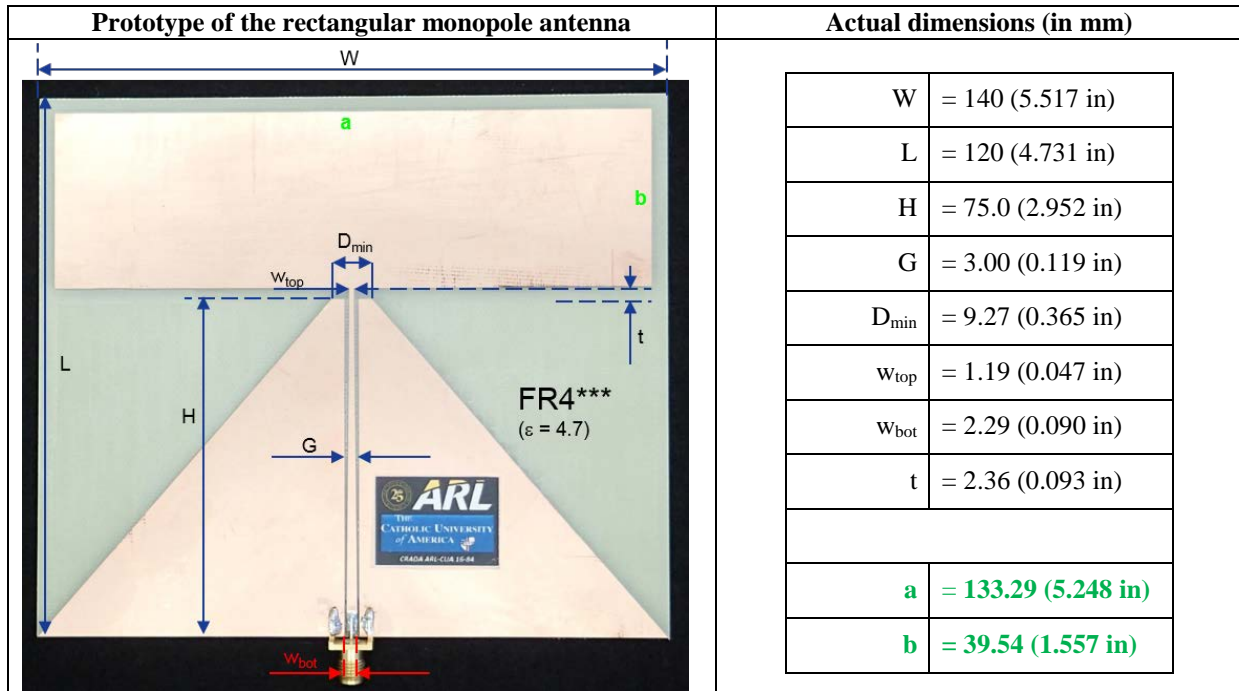


Fig. 5 Prototype of the rectangular monopole patch antenna with CPW feed and actual dimensions of the prototype

Figure 6 shows the reflection coefficients from the simulation. From 1 to 3 GHz, the return loss is below -10 dB. At 0.9 GHz, S_{11} is -5 dB, which can be acceptable, and S_{11} is high between 0.3 and 0.6 GHz. Figures 7 and 8 show the return loss of measured data of the prototype without and with absorber (RAM-AN77). The reflection coefficient of the prototype with the absorber is lower than the one without the absorber. With the absorber, S_{11} below -10 dB is from 150 MHz to 8.5 GHz, and there is the jump between 361 and 756 MHz with a peak at -6.91 dB, which is acceptable.

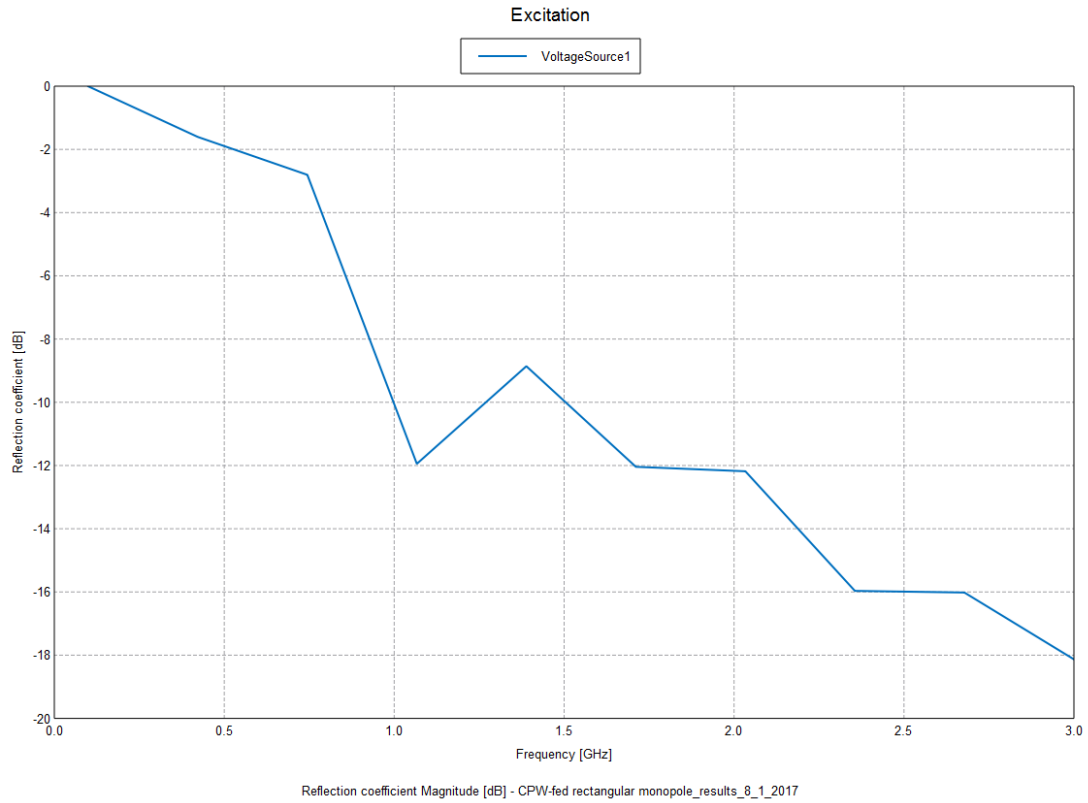


Fig. 6 Simulated reflection coefficients of the rectangular monopole patch antenna

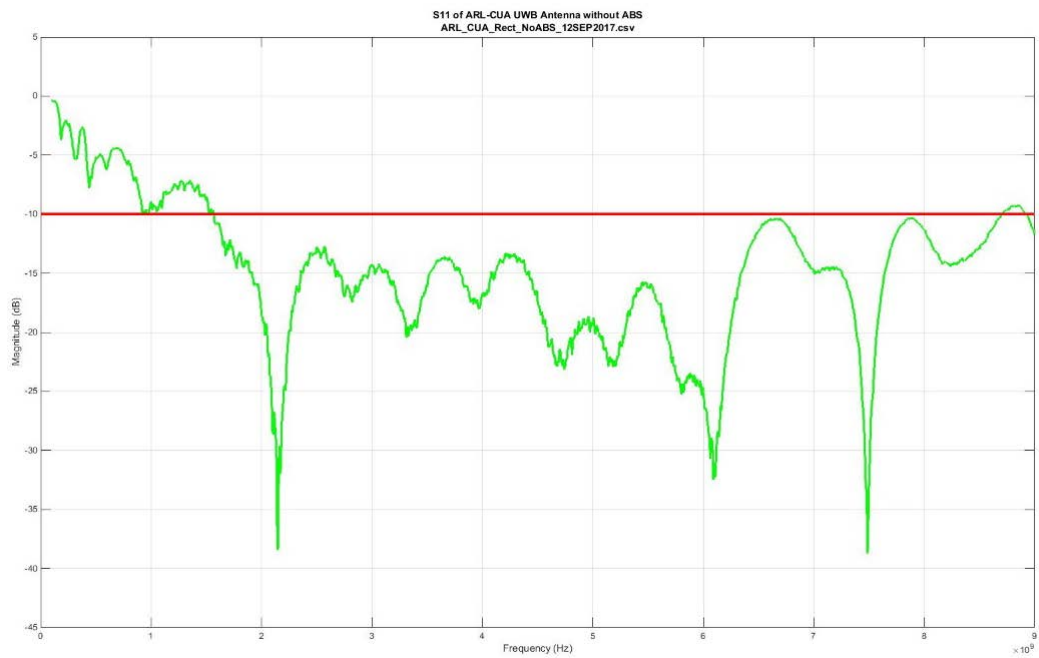


Fig. 7 Measured reflection coefficients of the rectangular monopole patch antenna without absorber

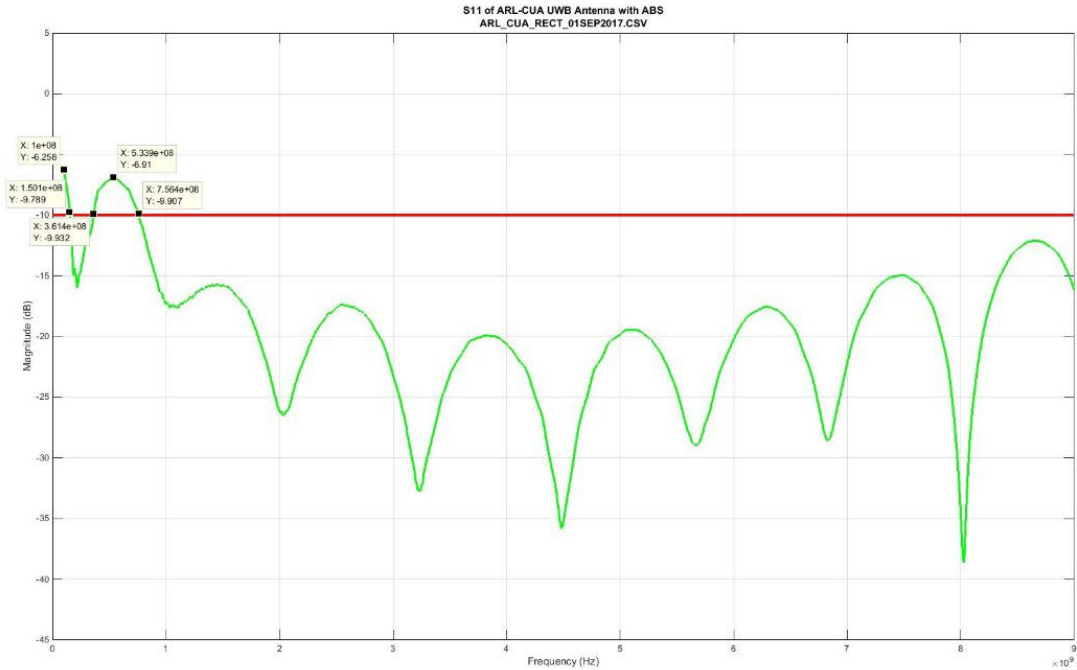


Fig. 8 Measured reflection coefficients of the rectangular monopole patch antenna with absorber

The radiation pattern from simulation results is also investigated. We have not had the chance to measure the far field of the prototype. Figures 9 and 10 show the simulation results of 3-D and 2-D radiation patterns at 0.1 and 1.066 GHz, respectively. The beamwidth of the antenna increases as the frequency increases such as at 0.1 MHz with 90° and 112° at 1.066 GHz. However, the beam starts to split at 1.7 GHz/about 44° as seen in Fig. 11.

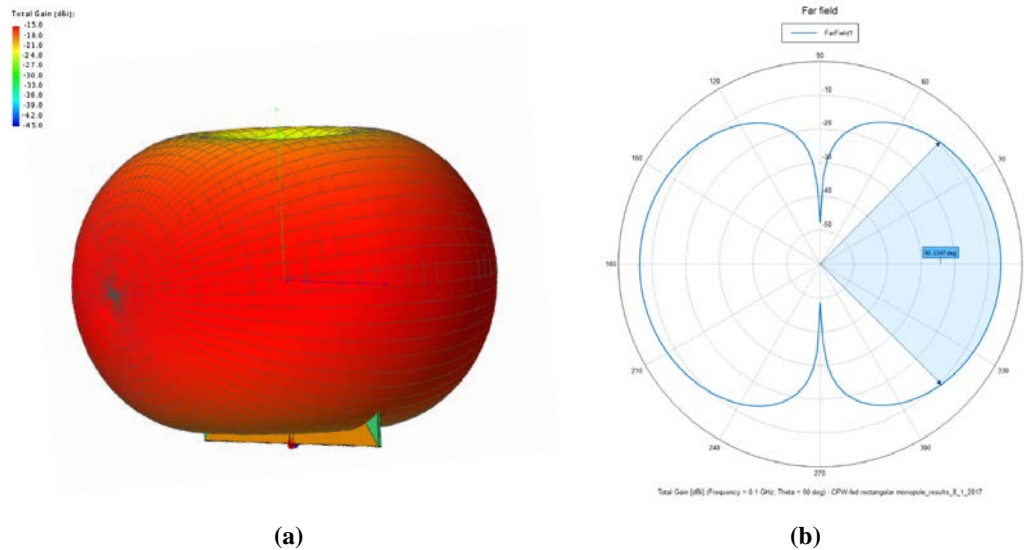


Fig. 9 Simulated radiation pattern of the rectangular monopole patch antenna at 0.1 GHz: a) 3-D pattern and b) 2-D pattern with theta = 90°

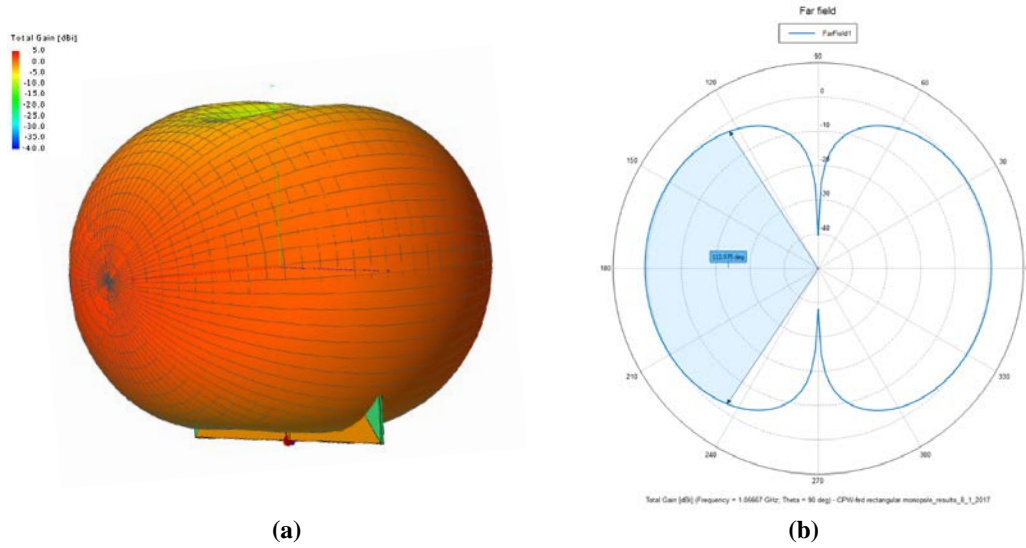


Fig. 10 Simulated radiation pattern of the rectangular monopole patch antenna at 1.0 GHz:
a) 3-D pattern and b) 2-D pattern with theta = 90°

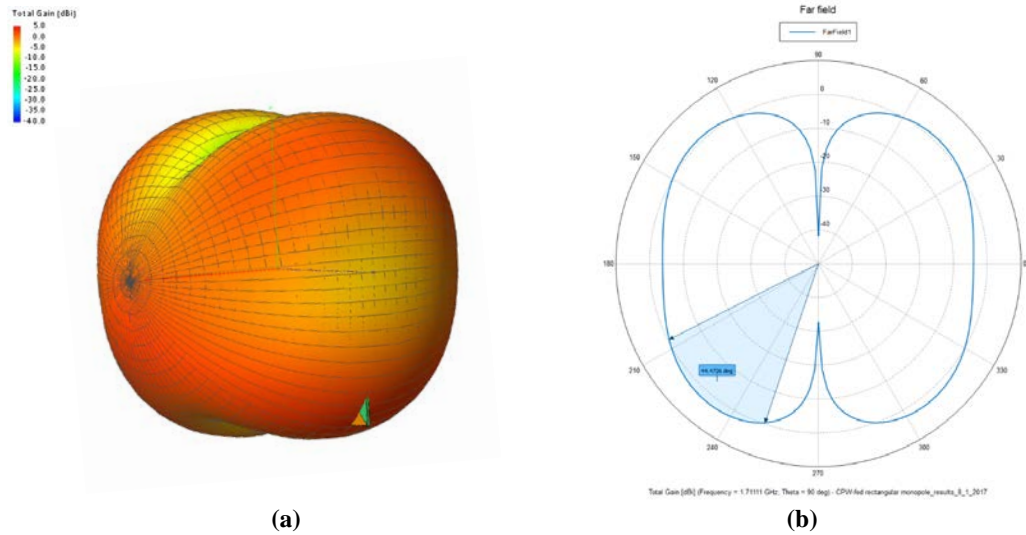


Fig. 11 Simulated radiation pattern of the rectangular monopole patch antenna at 1.7 GHz:
a) 3-D pattern and b) 2-D pattern with theta = 90°

4.2 Pixel Binary Patch Antenna

To further investigate the design of UWB antenna, the rectangular monopole patch antenna from the first design was discretized into small rectangular patches with 6 rows and 20 columns. All dimensions are the same as with the first designs. We used the binary PSO to optimize this design and used the same number of bees and iterations and optimized 120 binary numbers (either 0 or 1) corresponding to On or Off from 120 pixels on the rectangular patch. For each bee and at each frequency, 120 binary numbers are available to achieve the lowest return loss. The result after

optimizing the design is shown in Fig. 12. The return loss from the simulation is presented in Fig. 13. Compared with the simulation results from the original rectangular monopole patch antenna at Fig. 6, the return loss of this design is lower at lower frequencies such as -10 dB at 0.8 GHz.

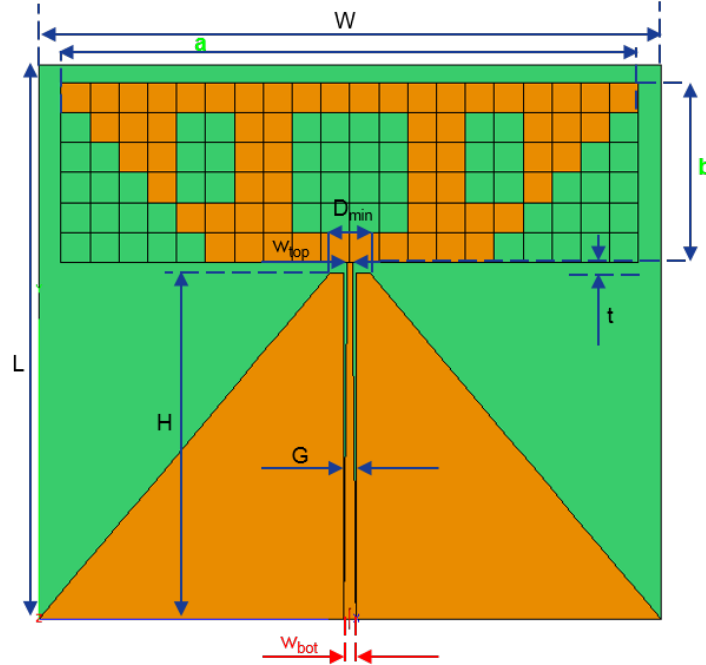


Fig. 12 Pixel binary patch array antenna

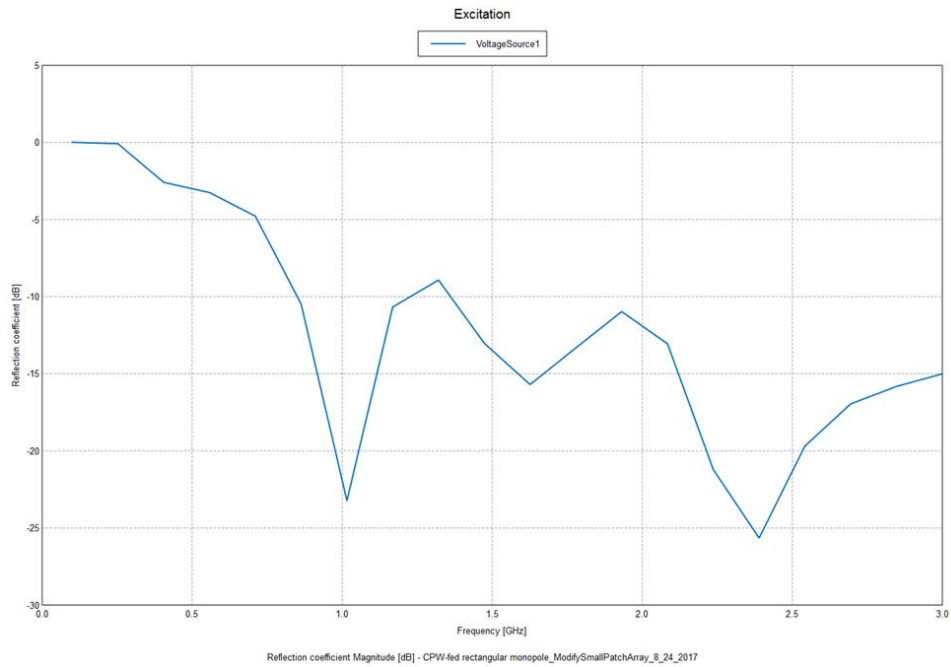


Fig. 13 Simulated reflection coefficients of the pixel binary patch antenna

The radiation patterns of the simulation results are presented in Figs. 14–16. The beam-width increases from 0.1 to 1 GHz (90° to 107°) until the beam is split at 1.6 GHz with 57° . The prototype of the pixel binary patch antenna was fabricated, as shown in Fig. 14, as FR4, $\epsilon = 4.7$, single-sided substrate.

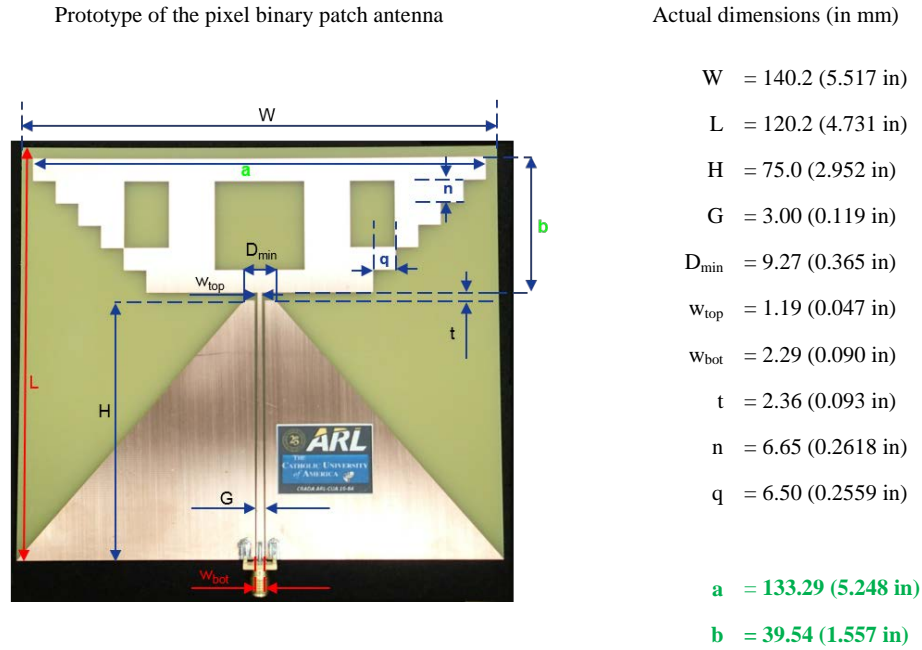


Fig. 14 Prototype of the pixel binary patch antenna with CPW feed and actual dimensions of the prototype

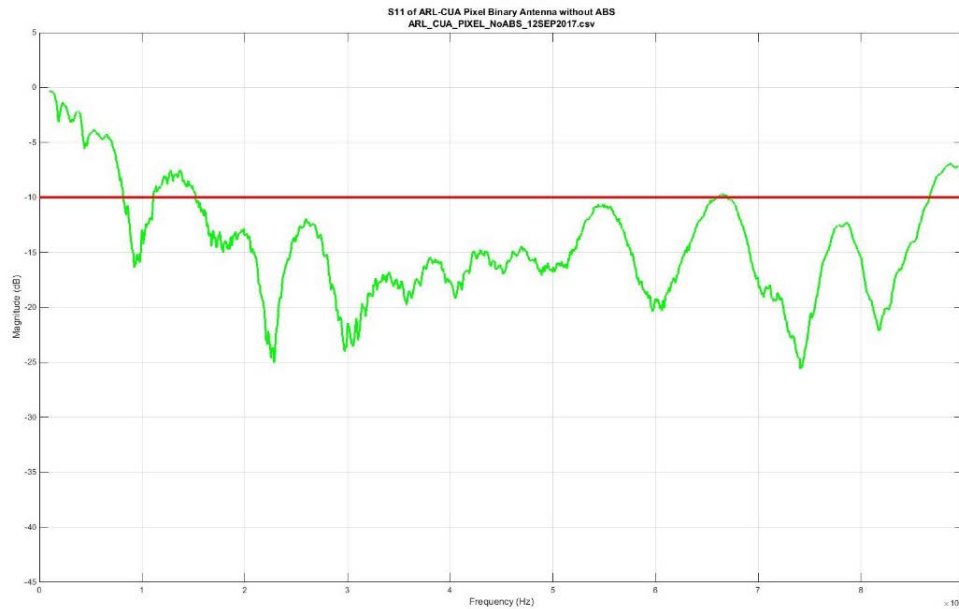


Fig. 15 Measured reflection coefficients of the pixel binary patch antenna without absorber

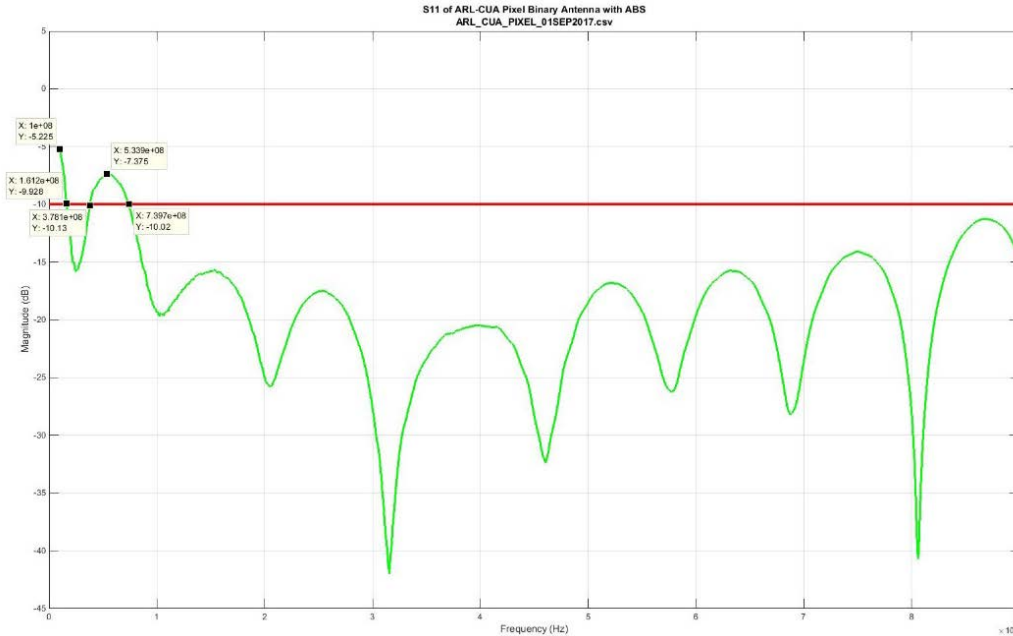


Fig. 16 Measured reflection coefficients of the pixel binary patch antenna with absorber (AN-77)

Figures 15 and 16 show the return loss of measured data of the prototype without and with absorber (RAM-AN77). The reflection coefficient of the prototype with absorber is lower than the one without absorber. With absorber, S11 below -10 dB is from 161 MHz to 9 GHz, and there is the jump between 376 and 739 MHz with a peak at -7.35 dB, which is acceptable.

The radiation pattern from simulation results was also investigated. We have not had the chance to measure the far field of the prototype. Figures 17 and 18 show the simulation results of 3-D and 2-D radiation patterns at 0.1 and 1.016 GHz, respectively. The beamwidth of the antenna increases as the frequency increases, such as at 0.1 MHz with 90° and 108° at 1.016 GHz. However, the beam starts to split at 1.6 GHz about 57.2° , as seen in Fig. 19.

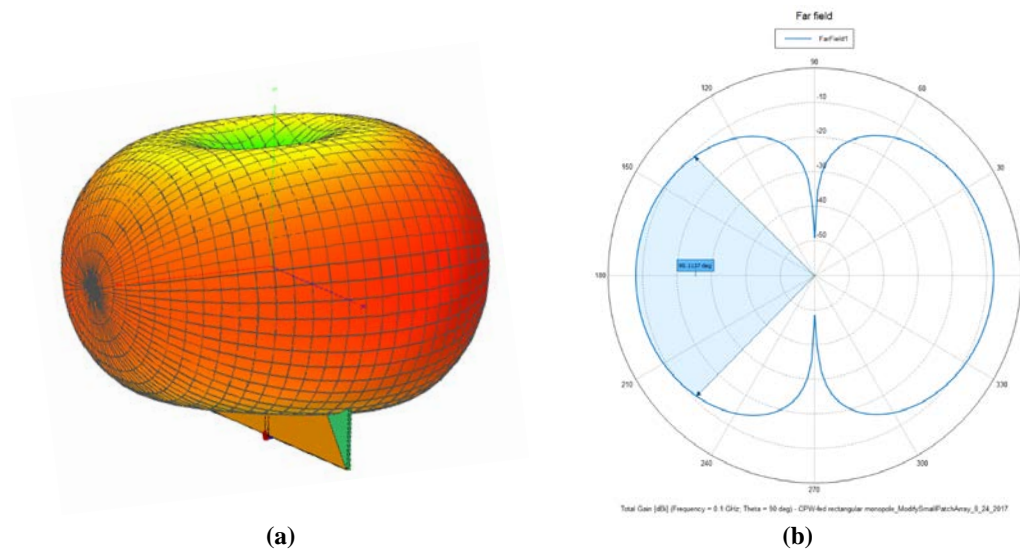


Fig. 17 Simulated radiation pattern of the pixel binary patch antenna at 0.1 GHz: a) 3-D pattern and b) 2-D pattern with $\theta = 90^\circ$

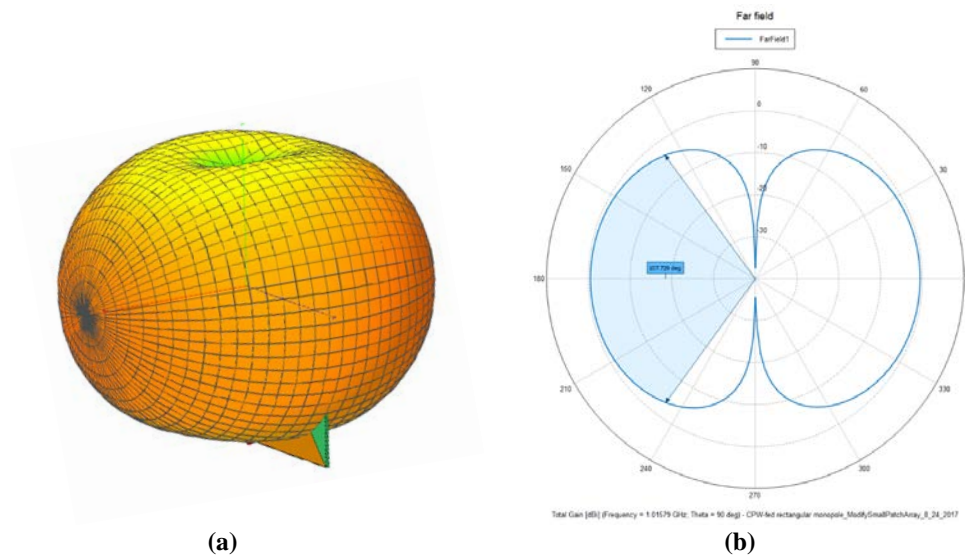


Fig. 18 Simulated radiation pattern of the pixel binary patch antenna at 1.016 GHz: a) 3-D pattern and b) 2-D pattern with $\theta = 90^\circ$

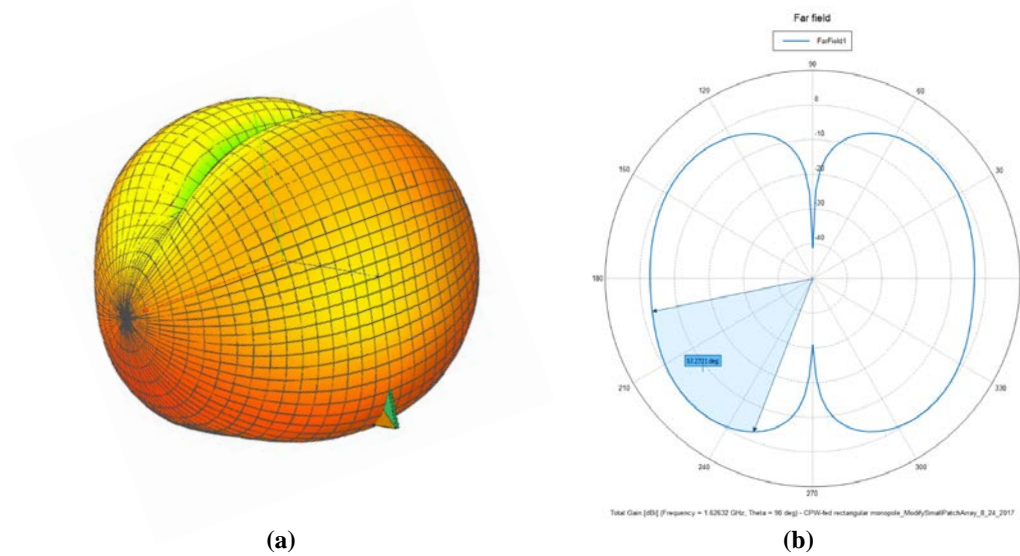


Fig. 19 Simulated radiation pattern of the pixel binary patch antenna at 1.6 GHz: a) 3-D pattern and b) 2-D pattern with theta = 90°

Comparing those designs, we see clearly that based on the simulation results, the pixel binary patch antenna performs better than the rectangular monopole antenna in terms of return loss with the presence of the absorber. In terms of simulated patterns, the rectangular monopole performs better than the pixel binary antenna.

5. Conclusion and Future Work

This report describes the methodology using complex and complicated bio-inspired optimization algorithms for the design and development of a new and novel small UWB antenna for future small unmanned air vehicle systems. We used the PSO technique to investigate and simulate many antenna designs, 2 of which were finalized and shown in this report. They include optimized rectangular monopole patch antenna and the optimized pixel binary patch antenna. Based on the simulation results, the optimized pixel binary patch antenna with a CPW feed line achieved better return loss, S11. These 2 antennas have potential impacts for future advanced ground-penetrating radar systems.

Other designs will be presented in coming reports. The antenna gain and the beamwidth of an antenna will be constrained for optimization in the future investigations.

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List of Symbols, Abbreviations, and Acronyms

2-D	2-dimensional
3-D	3-dimensional
ARL	US Army Research Laboratory
CPW	co-planar plane wave
CUA	The Catholic University of America
EFP	explosively formed penetrator
$gBest/g_{bn}$	global best
GPSAR	ground-penetrating synthetic aperture radar
IED	improvised explosive device
MoM	method of moment
$pBest/p_{bn}$	personal best
PSO	particle swarm optimization
$rand()$	random number function
UWB	ultra-wideband
v_n	velocity of particle in the n th dimension
x_n	particle coordinates in the n th dimension

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